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IR radiation, ozone distribution, cloud top heights, the solar constant, and "sferics" figure in future satellite experiments

Physical measurements from meteorological satellites

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Extensive discussions of the meteorological observations successfully obtained from artificial satellites, including the photographs taken by the Tiros series and the radiometric measurements by Tiros and by Explorer VII, have been given elsewhere. The forthcoming Nimbus series of meteorological satellites will carry similar television and radiometric instruments. In addition, other experiments are being planned and further experiments of meteorological importance are under study.

One of these experiments involves indirect determination of the atmospheric temperature. The radiance of the atmosphere to space in the infrared depends on the transmittance and the temperature, by the well-known principles of radiative transfer. The transmittance of an atmospheric gas depends mainly on its vertical distribution and if, as in the case of carbon dioxide, one can assume a uniform mixture, the transmittance is known as a function of the pressure. From measurements of radiance at several wavelengths with different transmittances, one should be able to deduce the temperature of the atmosphere as a function of pressure.

In 1959, L. Kaplan suggested that the temperature structure of the atmosphere could be deduced from radiance measurements from a satellite in several narrow intervals of the 15-micron carbon dioxide band.[1] At a conference to discuss infrared satellite experiments, it was suggested that the most feasible instrument at the present time for carrying out the suggested measurements would be an infrared grating spectrometer with multiple detectors.

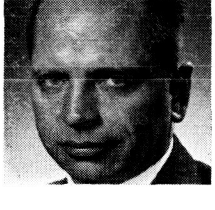
The Weather Bureau and NASA have proceeded with the development of an instrument of suitable bandwidth and radiometric accuracy. The first "breadboard" model has been produced and tested. The spectrometer, with its specially designed wedge-immersed thermistor detectors, has been described in detail elsewhere.[2] The photo on page 86 shows the spectrometer and gives a view of the grating and the detectors. The accompanying diagram shows the layout. An $f/5$ Ebert-type spectrometer of the "under and over" sort, it employs a grating 5 in. square that has a dispersion of about 1.4 cm^{-1} per mm at 15 microns. Exit slits are about 5 cm^{-1} wide, with the detector lenses situated behind the slits. In addition to four intervals in the 15-micron band, there is a fifth detector 7 cm^{-1} wide located in the 11.1-micron "window" whose purpose is to measure the temperature of the surface or cloud tops. A chopper wheel allows alternate views through "space" and "earth" ports.

This breadboard instrument has been used to conduct experiments from the ground, and has been found to perform approximately to the required radiometric accuracy. A report on its performance will be published in the near future. Currently under construction are instruments containing most of the design elements required for a satellite-borne instrument. These will first be tested in high-altitude balloons.

The spectrometer, however, is bulky (16 by 32 in.), heavy (55 lb, exclusive of electronics except the preamplifiers), and a heavy drain on power (10 w). Aboard a satellite, an interferometer would be more satisfactory from every standpoint. Although interferometer development is now considerably behind that of grating spectrometers, there is every promise that they will eventually achieve the spectral resolution and radiometric accuracy needed for indirect temperature soundings.

In the microwave region, the 5-mm band of oxygen might be employed for the same purpose, as suggested by Lilley and Meeks.[3] Discussions of some problems with indirect soundings will be found elsewhere.[4-7]

Microwave radiometry is another area of interest. The infrared region from 3–40 microns is presently the domain of many meteorological satellite experiments. The presence of atmospheric absorption bands of H_2O, CO_2, and O_3 make this region well suited for a variety of investigations. Furthermore, detectors are readily available and instrumental techniques fairly well established. But thermal emission at much longer wavelengths, in the regime of microwaves, also deserves attention. Some atmospheric constituents show a number of rota-



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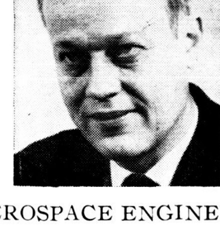

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tional lines there. Oxygen, for example, has a strong line at 2.5 mm and a band of 36 lines at 5 mm, while water absorbs at 0.85 and 13.5 mm.

The microwave range differs from the infrared by a factor of about 100 in the wavelengths. Theoretical concepts for experiments in the region of thermal emission are applicable to both infrared and microwave wavelength regions. However, the physical phenomena, and especially the instrumental techniques used, in both wavelengths make them distinctly different in many respects.

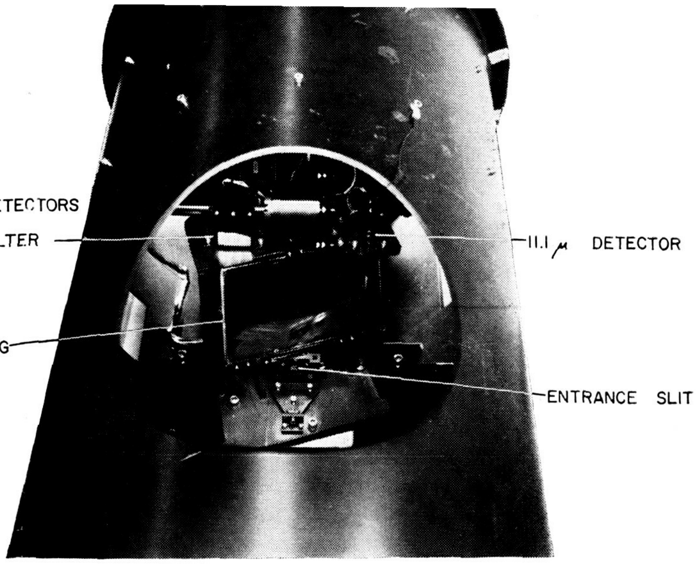
The longer microwaves penetrate clouds much easier than infrared rays. Only Rayleigh scattering must be considered for microwaves, since cloud droplets are very small compared to the wavelength. This is not necessarily so for larger rain drops, so that a method to detect precipitation in clouds may be based on this phenomenon. Furthermore, the high resolving power of microwave receivers and the existence of individual strong lines fairly isolated from others, removes some of the difficulties inherent in interpretation of infrared bands that consist of many overlapping lines of different strength.

These apparent advantages must be contrasted to certain drawbacks. In the infrared, the radiant emittance of a source, say at 250 K, is very sensitive to small temperature changes. The emittance in a narrow band near the 6.3μ water band, for example, is approximately proportional to the 10th power of the temperature. The same source shows a third power relation between emittance and temperature at 20μ. For microwaves, the signal strength is only linearly proportional to temperature.

The available emittance over useful ranges is orders of magnitudes lower at microwaves than at normally useful ranges in the infrared. This particular shortcoming, however, is compensated by the different operating concept of microwave receivers.

In the far infrared, the thermal detectors in use today register the radiation by means of the heating they undergo in absorbing the radiation. They are, however, affected by noise fluctuations which are the ultimate limitations on their sensitivity. In most instances, the noise is entirely unaffected by narrowband optical filters placed in front of them.

In contrast to this, the tuned circuit (cavity) of the microwave receiver (and other methods which restrict the effective bandwidth) short-circuits all frequencies not within its passband. This very effective reduction in noise makes possible microwave intensity measurements to an accuracy equivalent to a fraction of a degree centigrade.



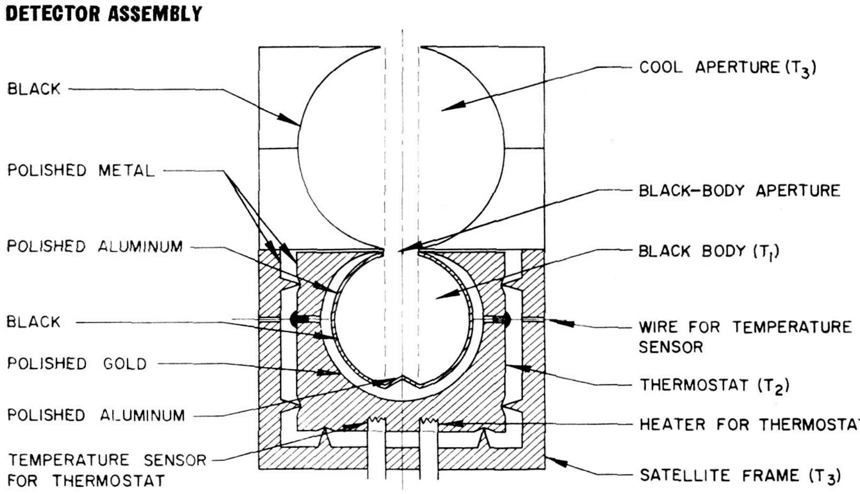
"Breadboard" Spectrometer photo above shows entrance slit, grating, detectors, and parts of viewing ports. The diagram on the opposite page shows side view of the spectrometer. The signal is the view out of the paper ("space") chopped against the view into the paper ("earth") as reflected off the mirror at the left, which here appears rotated to view a calibration black body.

Before useful meteorological experiments can be performed in this spectral range, many physical parameters must be considered. Absorption coefficients of atmospheric gases, extinction cross-sections of water droplets and ice crystals, the transmissivity of clouds and the emissivity of various types of terrain, plus state of the art of low-noise receivers, are important design criteria.

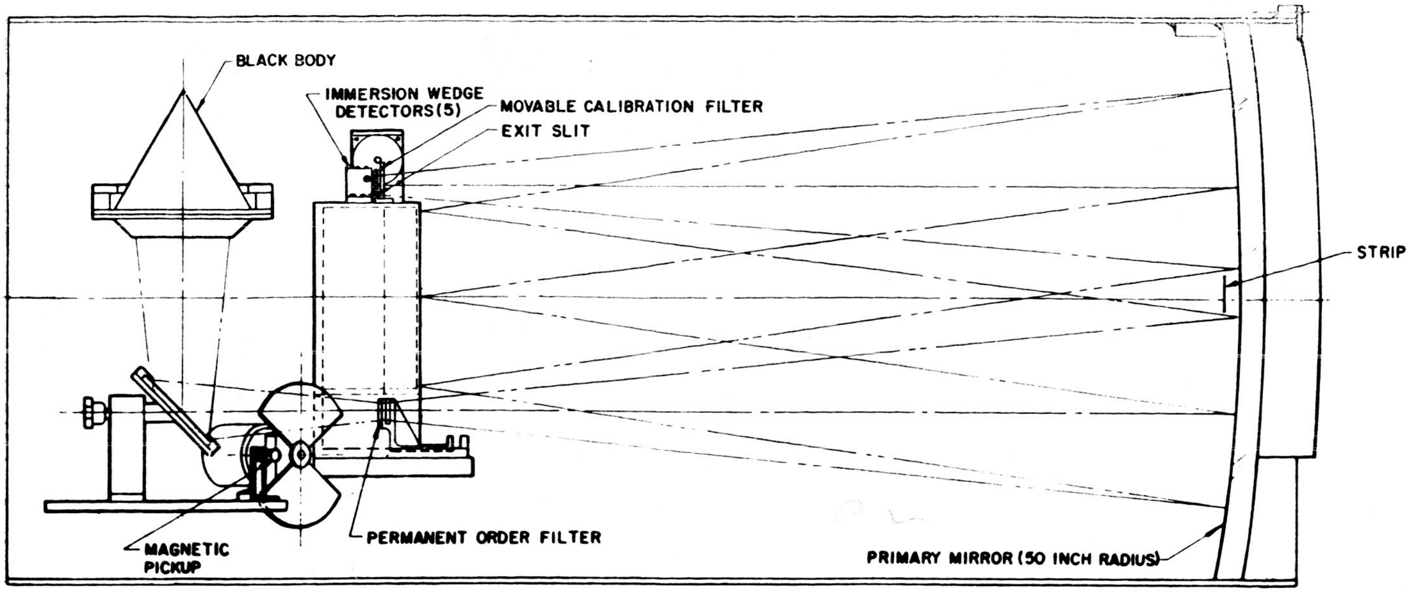
In much the same way that temperature structure can be obtained from a satellite, the distribution of ozone might also be found from measurements in the strong Hartley band in the ultraviolet. Because the transmittance of ozone is known, measurements of scattered sunlight at several wavelengths or of the occultation of direct sunlight by the atmosphere, at a series of positions of the satellite, can be used for the deduction of ozone distribution. Originally suggested by Singer,[8] this topic has been discussed in more detail by Singer and Wentworth,[9] Twomey,[10] and others.

Frith,[11] of the British Meteorological Office, suggested the occultation method; his instrument is to be carried in a satellite in the near future. Another instrument has been flown briefly in a polar orbiting satellite.[12] Each of these instruments employs a filter which admits a rather broad band in the ozone band below 3000 A. They are basically broadbeam receptors, in contrast with vertically viewing spectrometers considered for

DETECTOR ASSEMBLY



The black body is imbedded in, but thermally isolated from, a thermostat set to the wide range of expected operating temperatures. The cool aperture forms a black body for convenience.



ozone and temperature experiments.

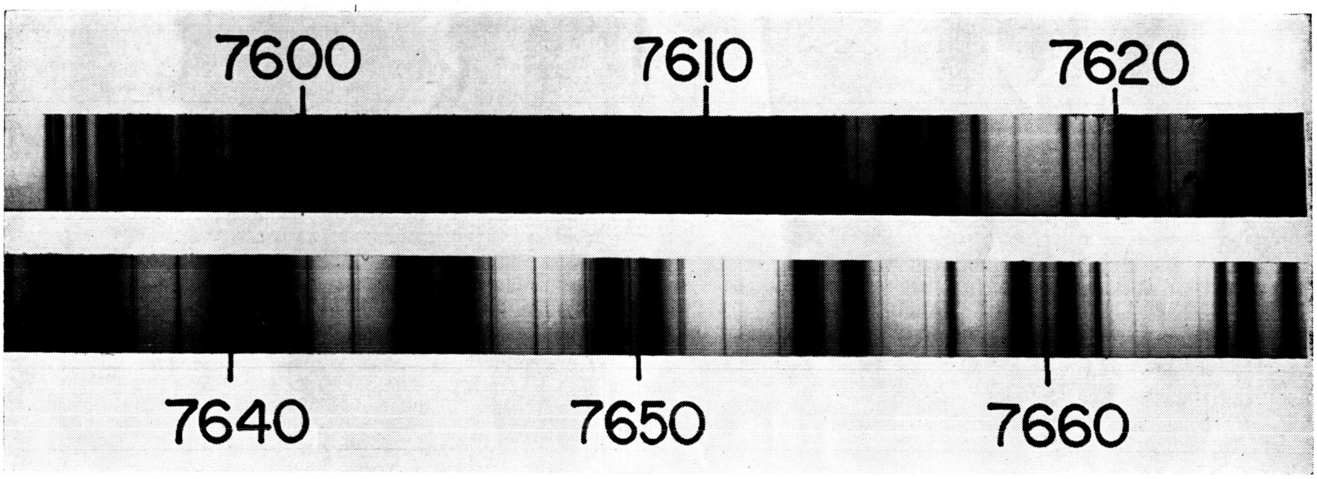
A wavelength scan for vertical viewing of scattered sunlight would require a spectrometer (or interferometer) with a resolution of a few angstroms and a field of view of not more than about 0.04 steradians. Such instruments have been considered, but have not yet been implemented by the Weather Bureau or NASA.

In another area, measurements of reflected sunlight by a satellite instrument can indicate the presence of a cloud, but meteorologists also require a knowledge of the height of cloud tops. Infrared radiometric measurements can be used to determine cloud-top temperatures, but the relation between height (or pressure) and temperature in the atmosphere is highly variable. Another method, largely independent of the temperature variations is available to us.

If a gas has a known mixture in the atmosphere, the transmittance of sunlight from the top of the atmosphere down to a cloud, and back to a satellite, will depend (aside from a slight temperature term) upon the optical path, given by the pressure at the cloud top and the angles of incidence and view. The only unknown is the pressure at the cloud top, which can be deduced from transmittance as measured from the relative radiance in the band and in the nearby continuum.

This experiment was proposed by Hanel,[13] who suggested using the 2-micron band of carbon dioxide. Yamamoto and Wark[14] suggested that the 0.76-micron band of oxygen would be better. While the 1.8-micron band of water vapor overlaps the 2-micron band rather seriously, the oxygen band does not suffer from blending of other atmospheric bands. For high clouds or for low water-vapor content, the situation for the 2-micron band is more favorable, although high spectral resolution would be necessary to take advantage of this band.

The detail of the 0.76-micron band is shown at bottom. In the upper part is the R branch which contains the band head (left), the band center, and 3 lines of the P branch. Below is an additional part of the P branch. This spectrum was obtained with the 150-ft tower telescope at Mt. Wilson. Many details can be seen, including the lines due to the O^{17} and O^{18} isotopes. Using this and other spectra, a study is being conducted to determine all the



Spectrum of 0.76-Micron Oxygen Band, obtained with the 150-ft tower telescope at Mt. Wilson. In the upper part is the band head (left); the **R** branch lies between the band head and the band center; three lines of the **P** branch can be seen to the right of the band center. In the lower part are lines farther out in the **P** branch. The very narrow lines throughout are from the isotopic molecules $O^{16}O^{17}$ and $O^{16}O^{18}$. There are also some solar lines.

necessary physical parameters of the band and to calculate transmittance under the range of optical path found in the atmosphere.

The illustration shows that the R branch can become nearly totally absorbing, and therefore the transmittance becomes insensitive to optical path. In the P branch, there remain regions of rather great absorption, but, at the longer wavelengths, there is a region of significant but not overwhelming absorption where sensitive measurements of transmittance might be made. Where the optical path is short (vertical incidence off high clouds), the P branch may become too weak to allow good transmittance measurements, and the R branch could be the preferable region. Thus it would probably be better to monitor several regions of the spectrum to cover all ranges of transmittance to be encountered with changing cloud heights, sun angle and viewing angle. Because filters do not cut off sharply, this experiment might require a spectrometer of low spectral resolution.

There is as yet no active effort to build an instrument to carry out this experiment from a satellite. The study of the band must first be completed in order to set forth the instrumental requirements.

Another interesting experiment would deal with the solar constant.[15] The fraction of solar energy absorbed by the earth and its atmosphere is of great importance for the understanding of meteorological processes. Absorbed sunlight heats the atmosphere and surface, and provides the energy source for evaporation of water and atmospheric circulation. The amount of radiation absorbed by the earth can be determined from a satellite by measuring the incident and the reflected components of the solar flux.

So far, only the reflected component has been measured from meteorological satellites, but refinements in these measurements will soon reach the point where uncertainties in the incident radiation become appreciable, and both components (the incident and reflected flux) must be determined. This holds for certain narrow spectral regions of special interest, such as the strong absorption bands of ozone in the ultraviolet (2200–2800 A), as well as for total solar energy flux integrated from the ultraviolet to far infrared part of the spectrum.

The latter quantity, per unit area, and at the mean distance of the earth from the sun is the "solar constant." A numerical value of 1.94 cal min^{-1} cm^{-2}, or 1350 watt m^{-2}, is generally accepted today,[16-18] although a more recent survey indicates that 2 cal min^{-1} cm^{-2} is a better estimate.[19] These values were derived from measurements made in recent decades from the earth's surface. Atmospheric extinction, however, necessitates considerable correction of experimental results. The atmosphere is completely opaque to large portions of the ultraviolet and infrared spectrum.

Satellites now present the opportunity to determine the solar constant directly, without the interference of the atmosphere.

The method chosen for a future experiment exposes a black body to the sun, registers the equilibrium temperature of the body, and telemeters the data back to earth. In equilibrium, the incoming solar flux balances the black-body flux from the cavity which is well defined by Stefan-Boltzmann's law. The measurement of energy flux can thereby be reduced to a temperature measurement.

Certain precautions must be taken, concerning mainly the blackness of the body, the degree of isolation achieved, and the accuracy of the temperature sensing devices.

The principle of the instrumentation is shown on page 87. The black cavity is thermally insulated from its surrounding as much as possible. In addition, the net flux between the cavity and its mounting is made negligible by thermostating the housing to approximately the operating temperature of the black body.

One final experiment that might be mentioned involves the measurement of "sferics," or the RF emissions by lightning (from "atmospherics"). The detection and mapping of sferics could be an important contribution to meteorology by indicating areas of strong vertical motion related to tropical storm development and to other violent phenomena bearing on strong winds, heavy rainfall, and turbulence.

Following a discussion among experts to determine the necessity of satellite measurements of sferics,[20] and the instrumental requirements for such an experiment, the Weather Bureau has sought to establish a more firm design requirement. Although there are no commitments at present on an instrument of this sort, it has been suggested that a simple receiver of fairly broad bandpass (probably in the vicinity of 100 mc/s), and with an antenna pattern encompassing the entire visible earth, would be the proper initial experiment.

The experiments discussed here are part of a possible future effort in meteorological observations from satellites. They may eventually be flown as space becomes available, and other experiments, not discussed here, may also be carried on satellites. However, instruments for such experiments must be conceived well in advance of possible flights because of the long lead-time involved.

Some of the Tiros experiments and those planned for Nimbus will be continued on an operational basis. Others may have only limited observational requirements, and can be discontinued after objectives have been achieved. These can then be replaced by others, so that the vital requirements for flexibility in scientific investigation can be realized, and new ideas and concepts continually tested.

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